

ADDITIONAL n-TYPE LDD/POCKET IMPLANT
FOR IMPROVING SHORT-CHANNEL NMOS ESD ROBUSTNESS

FIELD OF THE INVENTION

The present invention is related in general to the
5 field of electronic systems and semiconductor devices, and
more specifically to structure and fabrication methods of
short-channel MOS transistors, which have an additional
implant under the LDD/pocket compared to standard
technology.

DESCRIPTION OF THE RELATED ART

Integrated circuits (ICs) may be severely damaged by
electrostatic discharge (ESD) events. A major source of
ESD exposure to ICs is from the charged human body ("Human
15 Body Model", HBM); the discharge of the human body
generates peak currents of several amperes to the IC for
about 100 ns. A second source of ESD is from metallic
objects ("machine model", MM); it can generate transients
20 with significantly higher rise times than the HBM ESD
source. A third source is described by the "charged device
model" (CDM), in which the IC itself becomes charged and
discharges to ground in the opposite direction than the HBM
and MM ESD sources. More detail on ESD phenomena and
25 approaches for protection in ICs can be found in A.
Amerasekera and C. Duvvury, "ESD in Silicon Integrated
Circuits" (John Wiley & Sons LTD. London 1995), and C.
Duvvury, "ESD: Design for IC Chip Quality and Reliability"

(Int. Symp. Quality in El. Designs, 2000, pp. 251-259; references of recent literature).

ESD phenomena in ICs are growing in importance as the demand for higher operating speed, smaller operating voltages, higher packing density and reduced cost drives a reduction of all device dimensions. This generally implies thinner dielectric layers, higher doping levels with more abrupt doping transitions, and higher electric fields - all factors that contribute to an increased sensitivity to damaging ESD events.

The most common protection schemes used in metal-oxide-semiconductor (MOS) ICs rely on the parasitic bipolar transistor associated with an NMOS device whose drain is connected to the pin to be protected and whose source is tied to ground. The protection level or failure threshold can be set by varying the NMOS device width from the drain to the source under the gate oxide of the NMOS device. Under stress conditions, the dominant current conduction path between the protected pin and ground involves the parasitic bipolar transistor of that NMOS device. This parasitic bipolar transistor operates in the snapback region under pin positive with respect to ground stress events.

The dominant failure mechanism, found in the NMOS protection device operating as a parasitic bipolar transistor in snapback conditions, is the onset of second breakdown. Second breakdown is a phenomenon that induces thermal runaway in the device wherever the reduction of the impact ionization current is offset by the thermal generation of carriers. Second breakdown is initiated in a device under stress as a result of self-heating. The peak NMOS device temperature, at which second breakdown is

initiated, is known to increase with the stress current level.

Many circuits have been proposed and implemented for protecting ICs from ESD. One method that is used to improve ESD protection for ICs is biasing the substrate of ESD protection circuits on an IC. Such substrate biasing can be effective at improving the response of a multi-finger MOS transistor that is used to conduct an ESD discharge to ground. However, substrate biasing can cause the threshold voltages for devices to change from their nominal values, which may affect device operation. In addition, substrate biasing under steady-state conditions causes heat generation and increases power losses.

Solutions offered in known technology require additional IC elements, silicon real estate, and/or process steps (especially photomask alignment steps). Their fabrication is, therefore, expensive. Examples of device structures and methods are described in US. Patents # 5,539,233, issued 07/23/1996 (Amerasekera et al., "Controlled Low Collector Breakdown Voltage Vertical Transistor for ESD Protection Circuits"); # 5,793,083, issued 08/11/1998 (Amerasekera et al., "Method for Designing Shallow Junction, Salicided NMOS Transistors with Decreased Electrostatic Discharge Sensitivity"); # 5,940,258, issued 08/17/1999 (Duvvury, "Semiconductor ESD Protection Circuit"); # 6,137,144, issued 10/24/2000, and # 6,143,594, issued 11/07/2000 (Tsao et al, "On-Chip ESD Protection in Dual Voltage CMOS); and U.S. Patent Application # 09/456,036, filed 12/03/1999 (Amerasekera et al., "Electrostatic Discharge Device and Method").

The influence of substrate well profiles on the device ESD performance is investigated, for instance, in

SUMMARY OF THE INVENTION

5 A short-channel NMOS transistor in a p-well, bordered laterally on each side by an isolation region and vertically by a channel stop region, has a n-source and a n-drain, each comprising a shallow region extending to the transistor gate and a deeper region recessed from the gate, and both having a depletion region when reverse biased. The shallow regions are surrounded in part by an enhanced p-doping implant pocket. The transistor further has in these regions of enhanced p-doping another region of a p-resistivity higher than the remainder of the semiconductor. These regions extend laterally approximately from the inner border of the respective shallow region to the inner border of the respective recessed region, and vertically from a depth just below the depletion regions of source and drain to approximately the top of the channel stop regions.

15 According to the invention, these regions of higher p-type resistivity are created after gate definition by an ion implant of compensating n-doping, such as arsenic or phosphorus, using the same photomask already used for implants creating the extended source and drain and the pockets of enhanced p-doping.

20 In an ESD event, these regions of higher resistivity increase the current gain of the parasitic lateral npn bipolar transistor and thus raise the current I_{t2} , which initiates the thermal breakdown with its destructive localized heating, thereby improving ESD robustness.

25 When the gate, source and substrate terminals are at 0 V and the drain at positive potential, the current gain β

of the lateral bipolar npn transistor in the ESD event is defined as

$$\beta = (I_d - I_{gen}) / (I_{gen} - I_{sub}),$$

where I_d = drain current,

5 $I_{gen} = I_b + I_{sub},$

I_b = base current,

I_{sub} = hole current from the collector junction

through the substrate to the backside contact.

It is an aspect of the invention that the regions of
10 higher resistivity are the substrate of the transistor, enabling full functioning of the transistor while not affecting operation of neighboring active devices.

Another aspect of the invention is that the regions
15 of higher resistivity improve the ESD protection of the transistor without decreasing latch-up robustness or increasing inadvertent substrate current-induced body biasing of neighboring transistors.

Another aspect of the invention is that it is
20 equally applicable to PMOS transistors; the conductivity types of the semiconductor and the ion implant types are simply reversed.

The method of fabricating the regions of higher
resistivity under the active area of a high-voltage NMOS transistor having a gate comprises the steps of depositing
25 a photoresist layer over the transistor and opening a window in this layer over the active area of the transistor; then implanting, at high energy, n-doping ions into the p-type semiconductor substrate through the window, creating a deep region having a net p-type doping lower
30 than that of the p-type semiconductor remote from the transistor active area. A preferred depth of the regions

is between 50 and 150 nm. A region too deep would require higher implant energy with possibly more damage and thus higher junction leakage current or junction isolation failure.

5 It is an essential aspect of the present invention that this high-energy ion implant is performed without the need for a new photomask step. This economical feature renders the additional high-energy ion implant step of the present invention exceedingly inexpensive.

10 The technical advances represented by the invention, as well as the aspects thereof, will become apparent from the following description of the preferred embodiments of the invention, when considered in conjunction with the accompanying drawings and the novel features set forth in
15 the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified and schematic cross section through a lateral MOS transistor, illustrating the current flow at an electrostatic discharge event.

FIG. 2 is a schematic plot of drain (collector) current, on a logarithmic scale, as a function of drain voltage, on a linear scale, illustrating the onset of the second breakdown phenomenon.

FIG. 3 schematically presents a cross section of a lateral MOS transistor with a photoresist window opened for the high energy ion implant according to the invention.

FIG. 4 illustrates schematically, yet in more detail, the cross section of the regions of the compensating ion implant of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is related to U.S. Patent Applications # 60/263,619, filed on 23 Jan 2001 (Salling, "Structure and Method of MOS Transistor having Increased Substrate Resistance"), and # .. (TI-31089), filed on 28 May 2001 (Nandakumar et al., "Method of Channel Implant for Improving NMOS ESD Robustness").

The impact of the present invention can be most easily appreciated by highlighting the shortcomings of the known technology. The schematic cross section of FIG. 1 illustrates a commonly used integrated circuit (IC) component 100 in an ESD protection circuit, namely an NMOS transistor which operates in the mode of a lateral bipolar npn transistor during an ESD event and provides a low impedance current path to ground. The IC is formed in a semiconductor of a "first conductivity" type; in the example of FIG. 1, this "first conductivity" is p-type, the MOS transistor is an NMOS transistor, and the lateral bipolar transistor is a npn transistor. In present manufacturing, the first conductivity type semiconductor is created by the net doping due to a "substrate" and a "well".

As defined herein, the term "substrate" refers to the starting semiconductor wafer. In present manufacturing, the substrate typically has p-type doping. For clarity, this case is also selected as the basis for the following discussions. It should be stressed, however, that the invention and all description also cover the case where the substrate has n-type doping. In FIG. 1, the substrate is designated 101. Frequently, but not necessarily, an epitaxial layer 102 of the same

conductivity type as the substrate has been deposited over the substrate 101; in this case the term "substrate" refers to epitaxial layer 102 plus starting semiconductor 101. For the conductivity example selected for FIG. 1, a p-well 103 has been formed by localized acceptor ion implantation and annealing. An n-plus source region 104 (the emitter of the bipolar transistor) and drain region 105 (the collector of the bipolar transistor) were formed by shallow ion implants of donors. The surface between the emitter 104 and the collector 105 is covered by gate oxide layer 106. Layers 107, 108, 109, and 110 provide metallic contacts to the gate, emitter, collector and the wafer backside, respectively.

FIG. 1 further shows that emitter 108, gate 107 and wafer backside 110 are electrically connected to ground potential (0 V). A positive voltage spike at the collector, as caused by an ESD event, applies a reverse bias to the collector/base junction; the base is the substrate 101 (in some devices, epitaxial layer 102 plus the substrate 101); the depletion layer of the space charge region is designated 120. When the electric field in the depletion region 120 exceeds the breakdown field, avalanching occurs and forms electron/hole pairs. Electrons flow into the collector, and holes flow into the p-type base.

This hole current I_{sub} flows from the collector junction through the substrate to the backside contact 110, causing a voltage drop across the resistors R_{pwell} and R_{sub} , which positive (forward) biases the emitter/base junction. This emitter forward bias is proportional to the effective "substrate resistance" equal to the sum of the resistance components in the current path, which are

schematically shown as R-pwell and R-sub in FIG. 1. Those of the electrons injected from the emitter into the base which reach the collector depletion layer will participate in the avalanche mechanism.

5 The electron concentration will be multiplied in accordance with the electric field dependent avalanche multiplication factor. The resulting reduction of the device impedance is reflected in a "snap back" 201 in the current-voltage characteristic, which corresponds to a
10 "turn on" of the bipolar transistor. FIG. 2 plots the collector (or drain) current I (on a logarithmic scale) as a function of drain voltage V (on a linear scale). As illustrated in FIG. 2, this snap-back 201 occurs at the collector/drain voltage V_{t1} with an associated collector/
15 drain current I_{t1} . The field dependence of the avalanche multiplication factor is responsible for establishing a new stable current/voltage equilibrium 202. At high electron injection levels, base conductivity modulation also contributes towards making the device impedance positive again. It should be mentioned that the lateral npn
20 transistor also protects against negative ESD pulses. The collector 105 (in FIG. 1) now acts as emitter and diverts the ESD current to the backside substrate contact 110 and to the now reverse biased emitter 104, which now acts as
25 collector.

The current carrying capability of the device is limited by thermal effects in the avalanching collector depletion layer. A number of effects (such as the increase of intrinsic carrier concentration, a reduced carrier
30 mobility, a decrease in thermal conductivity, and a lowering of the potential barrier for tunnel currents) contribute to the onset of the second (thermal) breakdown

(203 in FIG. 2). The second breakdown trigger current I_{t2} is very sensitive to the device design, especially the doping profiles. Second breakdown results in junction melting and in an irreversible increase in leakage currents. It must, therefore, be avoided for normal device operation.

It is important for the present invention to conclude from FIG. 1 and the above discussion of FIG. 2 that increasing the resistors R_{pwell} and/or R_{sub} will lead to an earlier turn-on of the emitter and to a reduction of the current contribution of the avalanche mechanism. This is reflected in an increase of the second breakdown threshold current I_{t2} . As was pointed out in the above-referenced publication by K. Bock et al., the p-well resistance R_{pwell} , and thus I_{t2} , can be modified by the p-well doping. However, known technology recommended only a lower substrate (or epitaxial) doping or a lower implant dose as methods to increase the p-well resistance.

The present invention discloses an additional, compensating n-type implant into the p-well to produce a lowly doped p^- -region below the MOS transistor depletion region and above the channel stop to improve the bipolar current gain β .

As defined herein, geometrical and positional terms such as "vertical", "below", "above", "shallow", and "deep", "top", "depth" are used with the active surface of the semiconductor as reference line. According to this definition, the surface has "horizontal" orientation. The integrated circuit is built into this active semiconductor surface. The schematic cross sections of FIGs. 1 and 3 illustrate these positional interrelations.

1 The structure of the modified p-well doping and p-
well resistance R-pwell according to the present invention
is described in FIGs. 3 and 4, and the flexible and
economical method for tailoring R-pwell according to the
5 invention is described in FIGs. 5 to 10. While the
examples depicted embody the experimental conditions for an
NMOS transistor, analogous considerations hold for the
conditions of a PMOS transistor.

FIG. 3 shows in simplified and schematic (not to
10 scale) manner a small portion of an IC having on its
surface an MOS transistor, generally designated 300, at a
certain stage of its fabrication process according to the
invention. The invention applies to NMOS as well as PMOS
transistors fabricated into semiconductor substrate
15 material. Here, the substrate comprises a semiconductor
wafer 301 of p-type doping (onto which, for some devices,
an epitaxial layer 302, also of p-type doping, has been
deposited). For clarity, the description and discussion of
the invention will be for a p-type semiconductor. However,
20 the invention is also applicable if an n-type substrate is
used. The semiconductor material may be silicon, silicon
germanium, gallium arsenide or any other semiconductor
material used in IC fabrication.

The resistivity of the semiconductor substrate, into
25 which the MOS transistor is fabricated, ranges from about 1
to 50 Ωcm (this is also the resistivity of the epitaxial
layer). A well 303 of a "first" conductivity type has been
fabricated into the substrate. In FIG. 3, window 330a in
photoresist 330 is used to create the p-well shown; in
30 other circuit designs, the p-well may extend further. For
an NMOS transistor, this "first" conductivity refers to p-

type, for a PMOS transistor, to n-type. Silicon dioxide isolation trenches 304 define the active area of the lateral transistor within the p-well. For the gate 305 of the short-channel MOS transistor, poly-silicon or another conductive material is usually chosen; its thickness 305a is commonly between 140 and 180 nm, and the width 305b less than 0.2 μm , typically 0.1 μm . The gate insulator 306 (silicon dioxide, nitrided SiO_2 , or others) has a physical thickness between 0.5 and 5 nm.

FIG. 3 shows a deep source 310 and an extended source 311, further a deep drain 312 and an extended drain 313. The extended source and drain are prepared by low-energy, shallow implants (depth typically between 25 and 40 nm), the deep source and drain by medium-energy implants (depth typically between 100 and 140 nm) as part of the process flow shown in FIGs. 5 to 10. For the fabrication by ion implantation, a window 330a in a photoresist layer 330 is used; window 330a determines the lateral extent and active area of the MOS transistor. The same photoresist and window are used for the additional p-type implant creating the medium-conductivity channel stop layer 320 and the threshold adjust implant directly under the gate (not shown in FIG. 3).

FIG. 3 further shows the enhanced p-doping implant regions 314, which surrounds part of the shallow source 311, and 315, which surrounds part of the shallow drain 313.

After definition of gate 305, the window 330a is further used for the high-energy, compensating n-type implant of the present invention. This implant is performed for modifying the well resistivity in two regions 370 and 371 to an average value at least an order of

p-resistivity extend laterally approximately from the inner borders (311a and 313a, respectively) of the respective shallow regions 311 and 313 to the inner borders (310a and 312a, respectively) of the respective recessed regions 310 and 312. The regions of higher p-resistivity extend vertically from a depth just below the depletion regions of source and drain (311b and 313b, respectively) to approximately the border of the regions of enhanced p-doping (314a and 314b, respectively). The depth of the regions 370 and 371 of higher resistivity is about 30 to 50 nm from the surface.

Comparing FIG. 4 with FIG. 1 indicates that the regions 470 and 471 of higher resistivity are in the locations where avalanche can be expected in case of ESD event. These regions are, therefore, optimally located to increase current spreading and β , and thus to avoid localized heating by second breakdown.

For NMOS transistors, the semiconductor well and substrate of the first conductivity type (p-type) (including any epitaxial layer) has dopant species selected from a group consisting of boron, aluminum, gallium, and indium. Source, drain, their extensions, and the region of higher resistivity within the semiconductor of the first conductivity type have a dopant species selected from a group consisting of arsenic, phosphorus, antimony, and bismuth.

For PMOS transistors, the semiconductor well of the first conductivity type (n-type) has dopant species selected from a group consisting of arsenic, phosphorus, antimony, and bismuth. Source, drain, their extensions, and the region of higher resistivity within the

semiconductor of the first conductivity type have a dopant species selected from a group consisting of boron, aluminum, gallium, indium, and lithium.

The precise selection of a successful dose and energy for the compensating implant depends on the p-well background and device operating conditions. For typical conditions, preferred doses are in the 2.0 to 5.0 E+12 cm⁻² range, and preferred energies in the 120 to 160 keV range. The maximum β achieved is between 60 and 100.

The method and process flow for fabricating an IC MOS transistor with increased substrate resistance is outlined in the schematic and simplified FIGs. 5 to 10 for the example of an NMOS transistor; analogous process steps apply for the fabrication of a PMOS transistor.

- FIG. 5: selecting a p-type semiconductor 501 as substrate; may be an epitaxial material;
- FIG. 5: forming non-conductive electrical isolation regions 504 into p-type semiconductor 501 for defining the lateral boundaries of the NMOS transistor active area;
- FIG. 6: depositing a first photomask layer 601 and opening a window 601a therein, exposing the surface of the area between the isolation regions;
- FIG. 6: implanting low-energy p-doping ions into the exposed surface area, creating a shallow layer 602 suitable for adjusting the threshold voltage;
- FIG. 6: implanting high-energy p-doping ions into the exposed surface area, creating the p-well 603;
- FIG. 6: implanting medium-energy p-doping ions into the exposed surface area, creating a deep layer 604

suitable as channel stop;

- FIG. 6: removing the first photoresist layer;
- FIG. 7: growing over the surface an insulating layer,
such as silicon dioxide, suitable as gate
dielectric 701, covering said transistor area;
- FIG. 7: depositing a layer of poly-silicon or other
conductive material onto the insulating layer;
- FIG. 7: protecting a portion of the poly-silicon and
etching the remainder thereof, defining the gate
area 702 of the transistor;
- FIG. 8: depositing a second photoresist layer and
opening a window therein, exposing the surface of
the area between the isolation regions;
- FIG. 8: implanting, at low energy, n-doping ions into
the exposed surface area, creating shallow n-
doped layers under the surface, suitable as
extended source 801 and drain 802 of the
transistor;
- FIG. 8: implanting, at medium energy, p-doping ions,
creating enhanced p-doping regions ("pockets",
"halos") 803 surrounding in part the shallow n-
doped layers 801 and 802 of extended source and
drain;
- FIG. 8: implanting, at high energy, n-doping ions into
the enhanced p-doping regions, partially
compensating the p-doping and thus creating, at
predetermined depth under the surface, regions
804 having a net p-doping lower than that of the
p-type semiconductor remote from the transistor
active area;
- FIG. 8: removing the second photoresist layer;

- FIG. 9: depositing conformal insulating layers of an insulator, such as silicon nitride or silicon dioxide, over the surface and directional plasma etching this insulating layers so that only side walls 901 around the poly-silicon gate remain;
- FIG. 9: depositing a third photoresist layer and opening a window therein, exposing the surface of the area between the isolation regions;
- FIG. 9: implanting, at medium energy, n-doping ions into the exposed surface area, creating an n-doped region that extends to a medium depth under the surface, suitable as deep source 902 and drain 903 of the transistor;
- FIG. 9: removing the third photoresist layer;
- FIG. 10: forming silicides 1001, 1002, and 1003;
- forming contacts; and
- depositing the metallizations.

It is advisable to add the process step of annealing the high energy implant at elevated temperature. Of course, the process steps can be modified by implanting the n-doping ions at high energy after the process step of implanting the n-doping ions at medium energy.

For fabricating a PMOS transistor according to the method of the present invention, the flow of the above process steps applies in analogous fashion with a reversal of conductivity types.

While this invention has been described in reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention,

